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THE DEFORMATION OF THE GEOMAGNETIC FIELD BY THE SOLAR WIND

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ABSTRACT

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From the three-dimensional numerical solution to the Chapman-Ferraro problem of a steady solar wind perpendicularly incident upon a dipole field as obtained and described elsewhere, a simple spherical harmonic description of the distorted field is obtained. Using this description, a three-dimensional picture of the field-line configuration within the magnetosphere is given. The behaviour of the field lines on the daylight side changes abruptly as one approaches a critical latitude, which ranges between 82° and 86°, depending upon the intensity of the solar wind. Above this latitude, lines originating along the noon meridian pass over the North pole and cross the equator along the midnight meridian. The behaviour of conjugate-point phenomena and trapped particles near this critical latitude is discussed. Magnetic changes at the earth's surface due to an increase in the solar wind intensity are calculated. The diurnal variations due to a steady solar wind are calculated and found to be small compared with observed Sq fields.

AUTHOR

I. INTRODUCTION

This paper discusses a number of geophysical phenomena which are related to the presence of the solar wind and the resulting distortion of the geomagnetic field. A number of calculations will be made on the basis of a rather simple description of the distorted field given by an expansion in spherical harmonics. We shall consider the field as consisting of two parts: an internal part which will be represented by a simple dipole colinear with the earth's axis of rotation, plus an external part due to surface currents on the boundary of the magnetosphere. The external part will depend upon four spherical harmonic coefficients. The numerical values of these coefficients are obtained from a three-dimensional numerical solution to the Chapman-Ferraro problem of a steady solar wind perpendicularly incident upon a dipole field. The solution as obtained by Mead and Beard has been presented at meetings of the American Geophysical Union [Mead, 1962; Mead, 1963], and a separate paper containing a detailed report on the solution will be available shortly.

Many geophysical phenomena are related to the presence of a geomagnetic field extending into space. Our understanding of these phenomena, and our ability to describe them quantitatively often depends upon how accurately we can describe this field everywhere.

The method most commonly used to describe the geomagnetic field is to express it as the negative gradient of a scalar potential. This potential is given as the sum of a series of spherical harmonic functions with arbitrary coefficients. The values of the coefficients are usually determined by making an analysis of one or more components of the field at a large number of points on the surface of the earth. Such analyses have usually shown that only about 1 percent or less of the surface magnetic field can be of origin external to the earth. Near the earth, therefore, terms in the spherical harmonic expansion due to external sources can usually be safely neglected.

However, at large distances from the earth, the part of the field due to external sources becomes proportionately much larger. This is because terms in the magnetic field description associated with internal sources fall off as $1/r^3$ or faster, where r is the distance from the origin. On the other hand, the field associated with external source terms is either constant or proportional to positive powers of r.

For calculations of the magnetic field at large distances, therefore, it is important to have some knowledge of the external source terms. These sources fall into three main groups--ionosphere currents, ring currents due to trapped radiation, and currents due to the presence of the solar wind at the outer boundary of the magnetosphere.

Ionosphere currents are the source of most of the daily variations in magnetic field elements observed at the surface of the earth. However, outside the ionosphere, these become internal sources, and therefore the associated field falls off rapidly along with the main field. They therefore do not contribute much to the field at large distances.

Ring currents associated with the longitudinal drift of radiation belt particles have long been postulated as the current source producing the main phase of magnetic storms. However, the location and intensity of these currents have not yet been firmly established, and lacking such knowledge it is difficult to include them in any calculation of magnetic fields in space.

This paper is concerned with the effects of the third source, i.e., currents at the boundary of the magnetosphere. Using a spherical harmonic description of the distorted field, a three-dimensional picture of the field lines is presented. A number of interesting results which emerge from this picture are discussed. In particular, the shape of the lines and the magnitude of the field along the lines in the polar region bear upon the trapping of charged particles in this region. The behavior of conjugate point phenomena also changes rapidly in this region.

By varying the intensity of the solar wind, one can calculate the changes in the magnetic field components at varying positions on the surface of the earth. This can then be related to the sudden commencement phase of magnetic storms, which is usually considered to be due to an increase in the solar wind. And finally, we calculate the daily variation in the earth's field at various latitudes due to the presence of a steady solar wind, and compare this with the observed S_q (solar quiet) fields.

II. A Spherical Harmonic Description of the Distorted Field

We wish to express the geomagnetic potential in terms of sources within the earth plus current sources at the boundary of the magnetosphere. The choice of azimuthal angle, however, is different for these two sources. The terms in the expansion due to internal sources depend upon geographic longitude, whereas we shall assume that the surface current fields depend only upon the position of the sun, i.e., local time. If we assume that the region between the earth's surface and the magnetosphere boundary is source-free--that is, if we neglect ionsphere currents and ring currents--then the total geomagnetic potential V_T within this region may be expressed in terms of a spherical harmonic series

$$V_T = a \sum_{n=1}^{\infty} \left[\left(\frac{a}{r}\right)^{n+1} T_n(\theta, \alpha) + \left(\frac{r}{a}\right)^{n} \overline{T}_n(\theta, \varphi) \right]$$

$$= V(r, \theta, \alpha) + \overline{V}(r, \theta, \varphi) \qquad (1)$$

where a is the mean radius of the earth, r the distance from the earth's center, θ the colatitude, α the geographic east longitude and φ the local time measured from the <u>midnight</u> meridian. Throughout this paper barred quantities are those related to external sources. Here

$$T_n = \sum_{m=0}^{n} (g_n^m \cos m\alpha + h_n^m \sin m\alpha)\, P_n^m(\cos\theta) \qquad (2)$$

and

$$\bar{T}_n = \sum_{m=0}^{n} (\bar{g}_n^m \cos m\varphi + \bar{h}_n^m \sin m\varphi) P_n^m (\cos\theta) \tag{3}$$

where

$$P_n^m(\cos\theta) = \left[2\frac{(n-m)!}{(n+m)!}\right]^{\frac{1}{2}} P_{n,m}(\cos\theta) \qquad m > 0 \tag{4}$$

$$P_n^m(\cos\theta) = P_{n,m}(\cos\theta) \qquad m = 0 \tag{5}$$

and

$$P_{n,m}(x) = \frac{1}{2^n\, n!}(1 - x^2)^{m/2} \frac{d^{n+m}}{dx^{n+m}} (x^2 - 1)^n \tag{6}$$

Note that the Associated Legendre functions used in this paper (P_n^m) are those with the Schmidt normalization, as has been the convention in geomagnetic applications.

The three components of the magnetic field at all points inside the magnetosphere are then given by taking the negative gradient of V_T, viz.,

$$B_r = -\frac{\partial V_T}{\partial r} = -Z \tag{7}$$

$$B_\theta = -\frac{1}{r}\frac{\partial V_T}{\partial \theta} = -X \tag{8}$$

$$B_\varphi = -\frac{1}{r\sin\theta}\left(\frac{\partial V}{\partial \alpha} + \frac{\partial \overline{V}}{\partial \varphi}\right) = Y \tag{9}$$

where X, Y, and Z are the north, east and downward vertical components of the field, respectively.

For the calculations in this paper, we shall make certain simplifications. First of all, we shall assume that the internal earth's field is a pure dipole whose axis is colinear with the axis of rotation. This is equivalent to setting all internal coefficients to zero except g_1^0, which we shall set equal to 0.31 gauss.

Secondly, we shall assume that the direction of the solar wind is perpendicular to the dipole axis and parallel to the earth-sun line. With these assumptions, the magnetosphere and its associated field have two planes of symmetry, the equator and the noon-midnight meridian. In particular, B_r and B_φ are anti-symmetric about the equator, and B_φ is also anti-symmetric about the noon meridian. B_r and B_θ are symmetric about the noon meridian, and B_θ is also symmetric about the equator. Mathematically, this is equivalent to setting three-quarters of the external coefficients equal to zero. In particular, all the $\overline{h}$'s vanish, and only those $\overline{g}$'s for which $n + m$ is odd will remain.

If we limit ourselves to values of n less than or equal to 3, the north, east, and vertical components, respectively, of the total magnetosphere field are as follows:

$$X = -B_\theta = \frac{0.31 \sin\theta}{r^3} - \bar{g}_1^0 \sin\theta + \sqrt{3}\, \bar{g}_2^1\, r\, (2\cos^2\theta - 1) \cos\varphi$$

$$- \frac{3}{2} \bar{g}_3^0\, r^2 \sin\theta\, (5\cos^2\theta - 1) + \frac{\sqrt{15}}{2} \bar{g}_3^2\, r^2 \sin\theta\, (3\cos^2\theta - 1) \cos 2\varphi \quad (10)$$

$$Y = B_\varphi = \sqrt{3}\, \bar{g}_2^1\, r \cos\theta \sin\varphi + \sqrt{15}\, \bar{g}_3^2\, r^2 \sin\theta \cos\theta \sin 2\varphi \quad (11)$$

$$Z = -B_r = \frac{0.62 \cos\theta}{r^3} + \bar{g}_1^0 \cos\theta + 2\sqrt{3}\, \bar{g}_2^1\, r \sin\theta \cos\theta \cos\varphi$$

$$+ \frac{3}{2} \bar{g}_3^0\, r^2 \cos\theta\, (5\cos^2\theta - 3) + \frac{3\sqrt{15}}{2} \bar{g}_3^2\, r^2 \sin^2\theta \cos\theta \cos 2\varphi \quad (12)$$

where r is now measured in units of earth radii. Note that these expressions are only good out to the boundary of the magnetosphere. Outside that point, the field is zero in the model which we use here.

To obtain numerical values for the external coefficients, we have used the solution to the problem of a uniformly-directed steady solar wind perpendicularly incident upon a dipole field as obtained by Mead and Beard. The details of this solution will be reported upon in a separate paper. Using the procedures developed there, we have calculated the vector field due to the surface currents at 90 points distributed at different values of r, θ, and φ inside the magnetosphere. We have then used a least squares fitting program to determine the best values of all coefficients up to a given maximum value of n. A number of results emerged:

1) The two most important coefficients were $\bar{g}_1^0$, which produces a constant field directed parallel to the dipole, and $\bar{g}_2^1$. All other coefficients gave fields down by an order of magnitude or more, even in regions near the boundary.

2) Using only 4 coefficients, viz., $\bar{g}_1^0$, $\bar{g}_2^1$, $\bar{g}_3^0$ and $\bar{g}_3^2$, all three components of the vector field due to surface currents can be matched to an accuracy of about ± 2% out to 0.5 r_b, and ± 5% out to 0.9 r_b both on the light side and the dark side of the earth, where r_b is the distance to the boundary along the earth-sun line.

The numerical value of the coefficients depends upon the intensity of the solar wind. This dependence can most easily be expressed through r_b, the distance from the center of the earth to the boundary in the solar direction. The solution we have obtained finds

$$r_b = 1.07 \left(\frac{M^2}{4 \pi m n v^2} \right)^{1/6} \tag{13}$$

where M is the earth's dipole moment and $2 m n v^2$ is the pressure of the solar wind upon the magnetosphere. If r_b is measured in units of each radii, the coefficients are as follows:

$$\bar{g}_1^0 = \frac{-0.277}{r_b^3} \text{ gauss} \qquad \bar{g}_3^0 = -\frac{0.012}{r_b^5} \text{ gauss}$$

$$\bar{g}_2^1 = \frac{0.108}{r_b^4} \text{ gauss} \qquad \bar{g}_3^2 = -\frac{0.024}{r_b^5} \text{ gauss}$$

If we take $r_b = 10$ earth radii, a typical value observed by Explorer XII [Cahill and Amazeen, 1963], this gives a field due to surface currents of 28 gammas in the vicinity of the earth and 46 gammas just inside the boundary in the solar direction, in addition to the earth's field (1 gamma = 10^{-5} gauss). In Figs. 1-3 the components of the surface current field, dipole field, and total field are plotted as a function of radial distance for different values of latitude and local time.

These fields may be compared with those of Beard and Jenkins [1962], who calculated the surface current magnetic field in the meridian plane. They assumed a hemispherical surface for the magnetosphere on the daylight side, and obtained a field of 14γ at the earth's surface and 35γ just inside the boundary in the solar direction when $r_b = 10R_E$.

Midgley and Davis [1963] have also obtained a solution to the problem of a dipole in a cold, field-free plasma wind, using a moment technique. They obtain an expression for the surface current field in the vicinity of the earth in cartesian coordinates. When the appropriate transformations are made to a spherical system, the four coefficients they obtained agree with our four to about 20%.

III. Field-line Configuration Within the Cavity

The description of the distorted dipole field as given in section II was used in making a number of field-line calculations. The calculations were performed by a numerical integration of the set of equations:

$$\frac{dr}{ds} = \frac{B_r}{B} \tag{14}$$

$$\frac{d\theta}{ds} = \frac{1}{r}\frac{B_\theta}{B} \tag{15}$$

$$\frac{d\varphi}{ds} = \frac{1}{r \sin\theta}\frac{B_\varphi}{B} \tag{16}$$

to obtain r, θ, and φ as a function of the parameter s, the distance along the field line. Here B is the magnitude of the field.

The field line configuration in the noon-midnight meridian plane for $r_b = 10\ r_E$ is shown in Figure 4. The field lines corresponding to a pure dipolar field are shown as dashed lines. A number of interesting results emerge:

1) As expected, the field lines at large distances are compressed on the sunlit side. Note, however, that the field lines on the dark side are also compressed, although not as much. In the past it has sometimes been supposed that the field lines on the dark side would be extended further out rather than compressed, a conclusion which

is not supported by the present analysis. Note that the effect of distortion is only evident for field lines emanating from a latitude greater than 60°, corresponding to $L > 4$, where L is the usual McIlwain parameter.

2) As one approaches the North pole along the noon meridian, a critical latitude is reached beyond which all field lines emanating from the surface of the earth are bent back over the North pole and cross the equator along the midnight meridian, then pass underneath the South pole and enter the earth again at the normal conjugate point.

3) The critical latitude at which this transition occurs is between 84° and 85°. If the intensity of the solar wind is reduced so as to make $r_b = 15\ R_E$, the transition occurs between 85° and 86°. If the intensity is increased, making $r_b = 5R_E$ the transition is between 82° and 83°. Thus we see that the critical latitude is not very sensitive to the intensity of the solar wind.

4) Those field lines emanating from the earth close to the critical latitude pass very near the so-called "null point", which separates field lines crossing the equator along the noon meridian from those crossing along the midnight meridian. At the null point the magnitude of the field is zero, and the boundary of the magnetosphere is tangential to the direction of the solar wind. Using the field description given here, the latitude of the null point is 71°, independent of the intensity of the solar wind. The distance from the center of the earth to the null point is given by

$$r_n = 0.93 \, r_b$$

5) The field lines which pass very near the null point pass just inside the boundary of the geomagnetic cavity. This provides a way of checking the internal consistency of our method ofderiving the fields--we can trace out the boundary of the magnetosphere by plotting the locus of the 84° field line and the 85° field line as the azimuthal angle is varied. Hones [1963] has in fact determined a boundary in this fashion, with a different description of the distorted dipole field than that used here. His results are qualitatively similar to ours. Our method is indeed internally consistent; the boundary as determined this way is very nearly the same as that which we determined in the solution to the magnetosphere problem.

6) Since our distorted field is symmetric about the equatorial plane, pairs of conjugate points will always have the same longitude and equal but opposite latitude. However, the nature of the conjugacy at latitudes less than the critical latitude is much different from that in polar regions, since the polar lines of force travel out to much greater altitudes and are always on the dark side of the earth. Since the field out there is known to be very weak and turbulent, above the critical latitude one would expect to find much less correlation between geomagnetic phenomena at conjugate points. In addition, above the critical latitude, lines of force emanating from the night side of the earth are shorter than those which emanate from the day side but which cross the equator on the night side. Thus at high latitudes one should find greater correlations between

phenomena at conjugate points at night than during the day. Wescott and Mather [1963] have examined magnetograms from high-latitude conjugate stations and have found just such a day-night effect. In this case the geomagnetic latitudes of the conjugate stations were 78.3°N and 79.0°S, somewhat less than the critical latitude found here. However, a day-night difference might still be expected, since the lines of force on the day side pass much closer to the null point, where the field is expected to be very weak and turbulent. Additional evidence for a sudden change in the character of magnetic activity as one approaches the critical latitude has been given by Lebeau and Schlich [1962], who compared magnetograms from two stations at geomagnetic latitudes 75.6°S and 78.3°S. They found the higher latitude station was relatively more disturbed at all times, but particularly at midday, when both stations experienced their maximum activity. The correlation between average activities at the two stations was highest at midnight (≈ 0.95) and lowest at midday (≈ 0.65). Both Wescott and Mather, and Lebeau and Schlich explained their results using arguments similar to those used here.

7) With the description of the distorted field used here, one can calculate the magnitude of the field everywhere along a field line. The results of such calculations are shown in Figures 5 and 6. The first figure shows the field along lines emanating from various latitudes on the midnight meridian. The numbers are not much different than those calculated from a pure dipole field. On the other hand, Figure 6, showing lines along the noon meridian, indicates an unusual

behavior setting in as one approaches the critical latitude. At latitudes of 75° and above, the minimum field is no longer at the equator, but at a high latitude near the null point.

A number of interesting consequences on trapped particle studies emerge from these results. First of all, one would expect that it would be very difficult to permanently trap particles along field lines above the critical latitude on the daylight side, because of the weak fields, long field lines, and high turbulence along parts of the field line. This conclusion would also apply to latitudes less than but close to the critical latitude on the day side. One might expect, for instance, that no particles would be stably trapped at latitudes above that at which the minimum field on the day side is no longer at the equator, i.e., 75° in this analysis.

These expectations are confirmed by satellite studies of trapped particles. As expected, most of the radiation is trapped at low and middle latitudes. No trapped particles have been found over the poles. From Injun I data O'Brien [1963] has found a large diurnal variation in the high latitude termination of trapped electrons. On the average, this cutoff was at around 75° in local day and 69° in local night. The 75° cutoff would be reasonable in view of the closeness to the critical latitude. Computations are now under way to determine the drift paths of these particles, assuming conservation of the first two adiabatic invariants, to see whether this effect is sufficient to cause the observed reduction in the high latitude cutoff on the night side.

All observations so far have been based on calculations of field lines and field magnitudes in the noon-midnight meridian. This is the easiest situation to visualize, since the φ component of the field vanishes here, and the field lines are all coplanar. As we move away from the noon meridian, the magnetosphere surface currents give rise to an azimuthal field component, which in general moves the equatorial crossing point of each field line away from the sun. The lines emanating from a given longitude are thus no longer coplanar and it becomes more difficult to illustrate their behavior. One way of seeing this effect is to view the field lines from a position above the North pole. The lines are then seen as projections upon the equatorial plane. A series of such views are shown in Figure 7, each of which shows different longitudinal lines emerging from a given latitude. As expected, the azimuthal change is greatest for high latitude lines. A line emerging from 80° latitude at a longitude 40° east of the noon meridian crosses the equator at 57° east longitude. The picture changes rapidly as the critical latitude is approached, and beyond this latitude all lines cross the equator within $\pm 65^\circ$ of the midnight meridian, regardless of the longitude from which they originated.

This same effect is shown graphically in Figure 8. Here the change in longitude at the equator is plotted as a function of the local time at the point where the lines emerge from the earth. Again, the difference between the 84° lines and the 85° lines is clearly seen.

IV. Sudden Commencement of Magnetic Storms

The effect of sudden commencements can be calculated using the present field description, if we ignore transient variations (such as those caused by the propagation of hydromagnetic waves) and assume that the entire magnetosphere adjusts at once to an increase in the intensity of the solar wind. The only effect is then to reduce all magnetosphere dimensions by a constant factor and increase the internal fields proportionately. Figure 9 shows the results of this calculation. Here we plot the field along the geomagnetic equator at the earth's surface due to the magnetosphere surface currents, as a function of r_b, the position of the boundary. If the boundary is at 10 earth radii, the magnetosphere field is 30 γ at noon, 28 γ at 6 p.m., and 26 γ at midnight. A sudden increase in the solar wind causing the boundary to shrink to 6 R_E would increase the field to around 130 γ, producing an observed increase of about 100 γ in the north component of the field at the geomagnetic equator. The energy density of the solar wind would have to be increased by a factor of around 20 to produce this change.

An approximate analytic expression for the latitude dependence can be obtained by taking only the leading term in the surface current field, i.e., the one proportional to $\bar{g}_1^0$. This term is independent of local time and we have

$$\Delta X \text{ (gammas)} = \frac{27{,}700}{r_{bo}^3}\left[\left(\frac{r_{bo}}{r_b}\right)^3 - 1\right] \cos\lambda \tag{17}$$

$$\Delta Z \text{ (gammas)} = -\frac{27{,}700}{r_{bo}^3}\left[\left(\frac{r_{bo}}{r_b}\right)^3 - 1\right] \sin\lambda \tag{18}$$

where r_{bo} is the quiet-time position of the boundary, and r_b is the new equilibrium position after the solar wind has increased. It is clear from this expression that an increase in the solar wind intensity will add to the north or X component of the earth's field, but oppose the earth's vertical component. This is true in both the northern and southern hemispheres.

This type of analysis cannot account for the main phase of magnetic storms, since the maximum decrease in the horizontal component would occur only if the solar wind were to vanish entirely. If the quiet-time boundary were at 10 R_E, the maximum decrease is only about 30 γ, whereas decreases of several hundred gamma are often observed. Thus, the current sources which produce the main phase of magnetic storms cannot be those at the magnetosphere boundary.

V. The Contribution to Sq Fields by the Solar Wind

Using the description of the distorted field in this paper, one can calculate the daily variation of the three components of the magnetic field at the surface of the earth for different latitudes. That is, we can calculate X, Y, and Z of (10 to 12) as a function of latitude λ (=90° -θ) and local time φ, for $r = 1$. This is equivalent to calculating the portion of the Sq (solar quiet) field due to surface currents at the boundary of the magnetosphere.

The results are shown in Figure 10 for $r_b = 10\ R_E$. The variation shown here is almost entirely due to terms proportional to $\bar{g}_2^1$. The $\bar{g}_1^0$ terms are time-independent, and higher-order terms are very small compared to the $\bar{g}_2^1$ terms at $r = 1$.

An approximate analytic expression for the daily variation produced by the solar wind may be obtained from Equation by keeping only those terms proportional to $\bar{g}_2^1$:

$$X\ (\text{gammas}) = -\frac{18{,}700}{r_b^4} \cos 2\lambda \cos\varphi \tag{19}$$

$$Y\ (\text{gammas}) = \frac{18{,}700}{r_b^4} \sin\lambda \sin\varphi \tag{20}$$

$$Z\ (\text{gammas}) = \frac{18{,}700}{r_b^4} \sin 2\lambda \cos\varphi \tag{21}$$

where the expressions are now in terms of the geomagnetic latitude λ instead of the co-latitude θ.

Figure 10 is qualitatively very similar to that obtained from a spherical harmonic analysis of the earth's Sq field performed by Chapman in 1919, and reported in Chapman and Bartels [1940, Vol I, p. 215]. This is due to the fact that in both cases the $\bar{g}_2^1$ term is the leading term and is of the same sign. However, there are three important differences:

1) The observed S_q field shows typical variations of 20-40 γ at mid-latitudes, whereas the S_q field produced by the solar wind as calculated here gives a variation of only 2-3 gammas. The boundary would have to be brought down to 5-6 R_E by the solar wind in order to produce changes as large as those actually observed.

2) The observed daily changes are much greater during the hours of sunlight than during those of darkness. This is not one of the results of the present analysis. Expressed in another way, terms of higher order than $\bar{g}_2^1$ are really much more important than those produced by surface currents only.

3) The present analysis does not predict the very large daily variations (100-200 γ) observed at stations very near the magnet equator, e.g., Huancaya, Peru.

We see, then, that although the calculated daily variations produced by the solar wind are qualitatively similar to those actually observed, they differ both in magnitude and in details. We conclude that the solar wind makes only a small contribution to the total S_q field. The major portion is almost certainly due to current systems in the ionosphere together with the associated induced earth currents.

VI. DISCUSSION AND CONCLUSIONS

There are a number of limitations in the accuracy of the field description used in this paper. First of all, the underlying assumptions are not fully met--we have assumed a steady solar wind, no magnetic field in the interplanetary region, specular reflection of the solar wind at the magnetosphere boundary, the absence of a shock wave or transition region, and perpendicular incidence upon a pure dipole colinear with the earth's axis of rotation. Secondly, we have not considered contributions from any external sources except those at the magnetosphere boundary. Third, we have assumed a completely non-conducting magnetosphere, whereas currents induced either in the earth's interior or the conducting ionosphere could modify the situation.

Despite these limitations, we feel that the present picture is at least qualitatively correct. The fact that the earth is not purely dipolar would alter the details, but not the main results. The presence of significant ring currents would change the field line picture, but there are indications that at least during quiet times, the surface current fields are the dominant external influence in the magnetosphere. Perhaps the most serious limitation is the assumption that the solar wind is perpendicular to the dipole. The dipole axis can be tilted as much as 35° either towards or away from the sun, depending upon time of day and time of year. In addition, the solar wind velocity vector may not be parallel to the earth-sun line. These conditions would remove the north-south and east-west symmetry conditions inherent in the present description. We are now attempting calculations on the more general situation.

Several conclusions stand out in the present analysis. We have found it possible to describe the earth's distorted field with reasonable accuracy using only a few numerical coefficients for the external surface current source terms. With this description, the field lines in the noon meridian plane exhibit some unusual characteristics as one approaches a certain critical geomagnetic latitude, which varies from 82° to 86°, depending upon the solar wind intensity. For lines emanating from points near to but less than this latitude, the minimum value of the magnitude of the field along the field line occurs at a high latitude near the null point, rather than at the equatorial crossing point, as one would ordinarily expect. Lines emerging beyond the critical latitude are bent over the north and south poles and cross the equator along the midnight meridian. Lines emerging near the critical latitude but off the noon meridian tend to be pushed back toward the dark side. At lower latitudes the presence of the solar wind compresses the field lines on both the dark side and the light side, although the effect is largest on the light side. The effect of the solar wind is only significant upon those lines emerging at latitudes greater than 60°. We have examined a number of consequences of this overall field line behaviour upon trapped radiation and geomagnetic activity.

The field description permits us to calculate the effects at the earth's surface due to an increase in the solar wind, as is observed during a sudden commencement. We find that the earth's horizontal component is increased, but the magnitude of the vertical component is decreased, in both hemispheres. The diurnal changes in the components of the earth's field due to rotation under a steady magnetosphere are calculated, and the resulting variations are found to be small as compared with the observed Sq fields, indicating that these fields are not primarily due to magnetosphere surface currents.

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FIGURE CAPTIONS

Fig. 1. Radial dependence of the surface current field, dipole field, and total field along the earth-sun line. Due to symmetry, only the X component is non-vanishing.

Fig. 2. Radial dependence of the field at dusk on the equator. At this longitude the boundary is at $1.35r_b$.

Fig. 3. Radial dependence of the field at $\lambda = 45^\circ$ along the noon meridian. The X component is strengthened, but the Z component is reduced by the surface currents.

Fig. 4. Field-line configuration in the noon-midnight meridian plane. With $r_b = 10R_E$, the critical latitude is between 84° and 85°. The dipole lines are compressed on both the daytime and the nighttime side.

Fig. 5. Absolute magnitude of the field along lines on the midnight meridian.

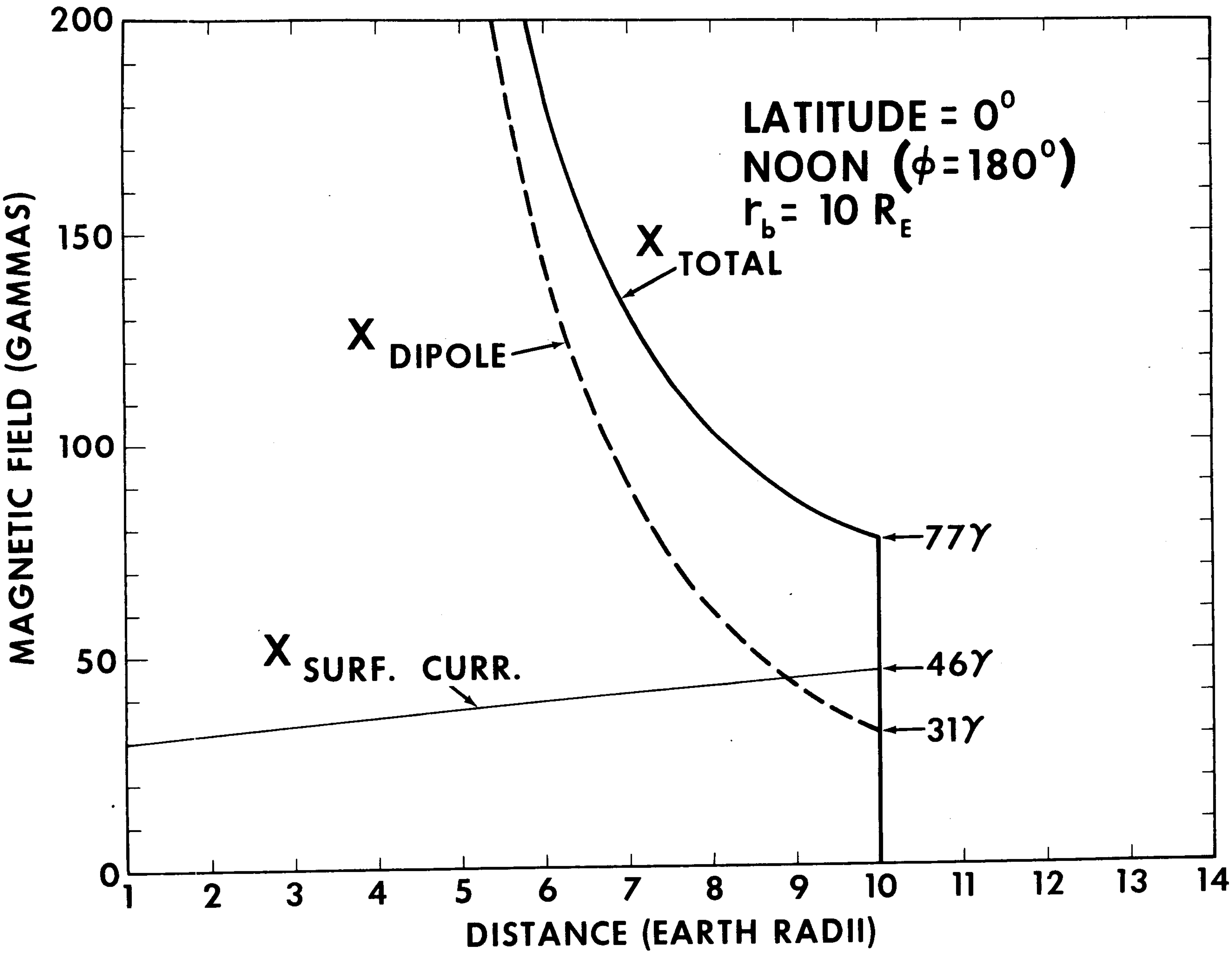
Fig. 6. Absolute magnitude of the field along lines on the noon meridian.

Fig. 7. View of the field lines from above the North pole. Since these are projections upon the equatorial plane, the field lines do not really cross as the 85° drawing would seem to indicate

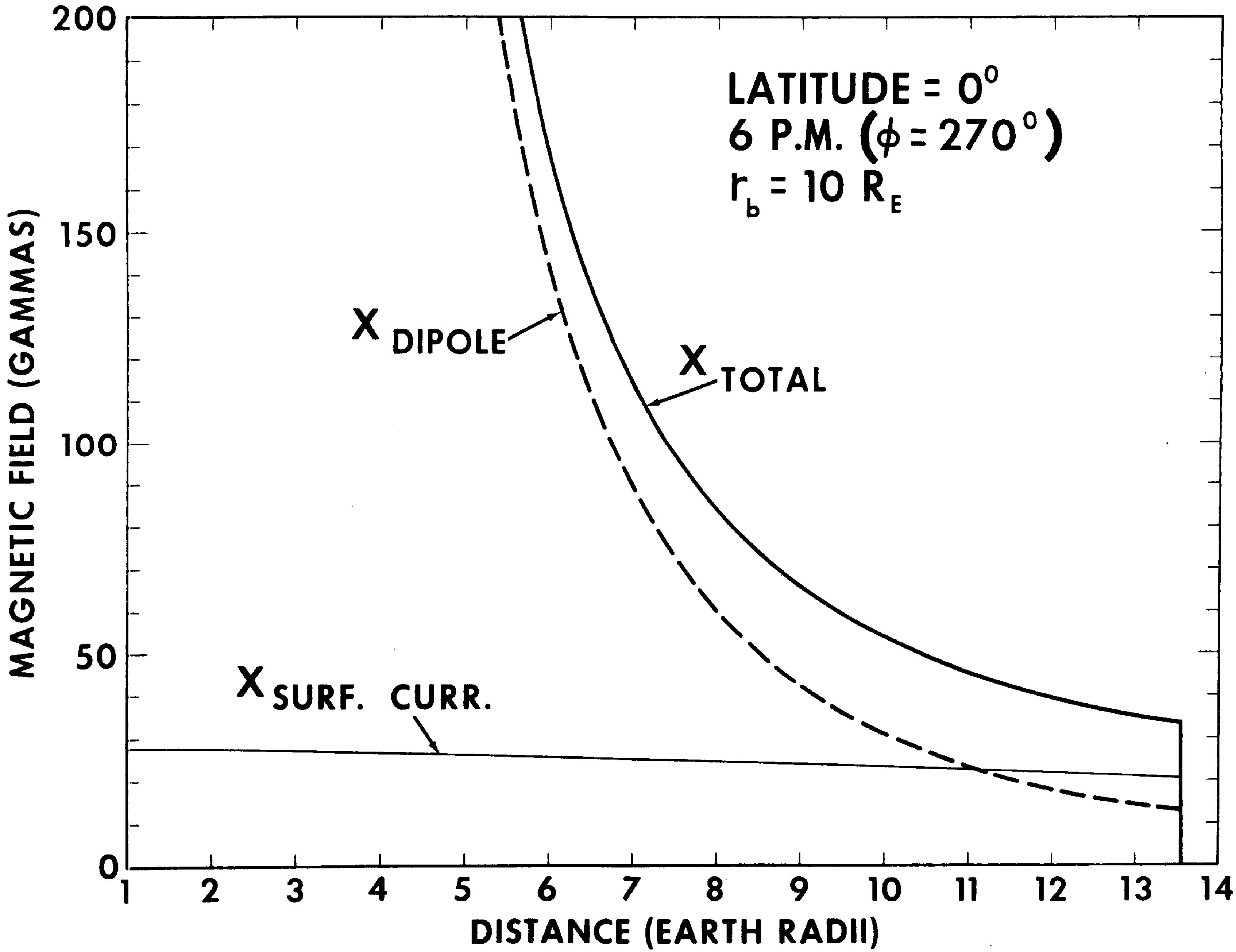
Fig. 8. Longitudinal change of the field lines at the equatorial crossing point.

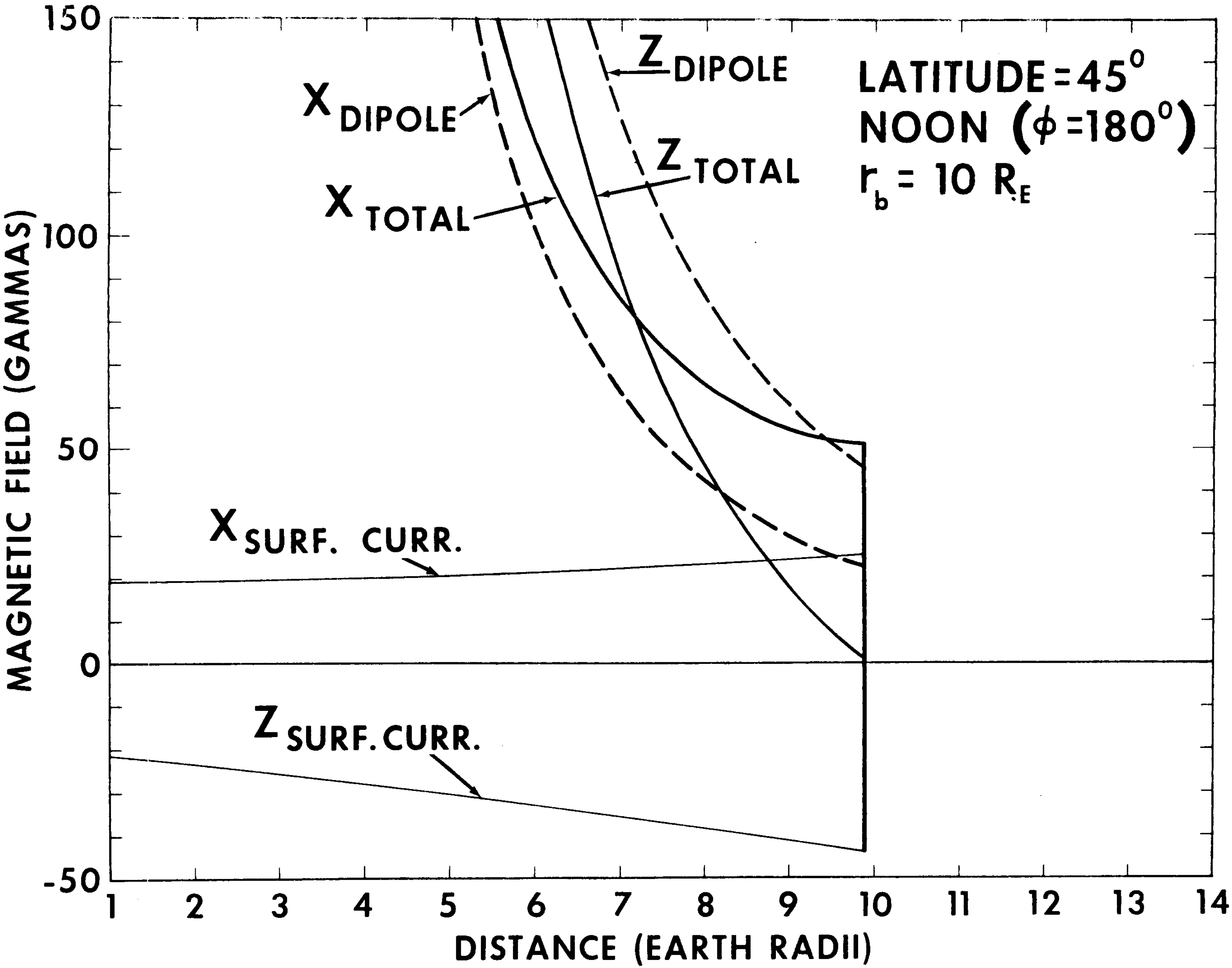
Fig. 9. Surface current field along the equator at the earth's surface as a function of the position of the boundary in the solar direction. From this the change in the earth's field during a sudden commencement can be related to a change in the position of the boundary.

Fig. 10. Diurnal variations in the earth's field due to a steady solar wind.

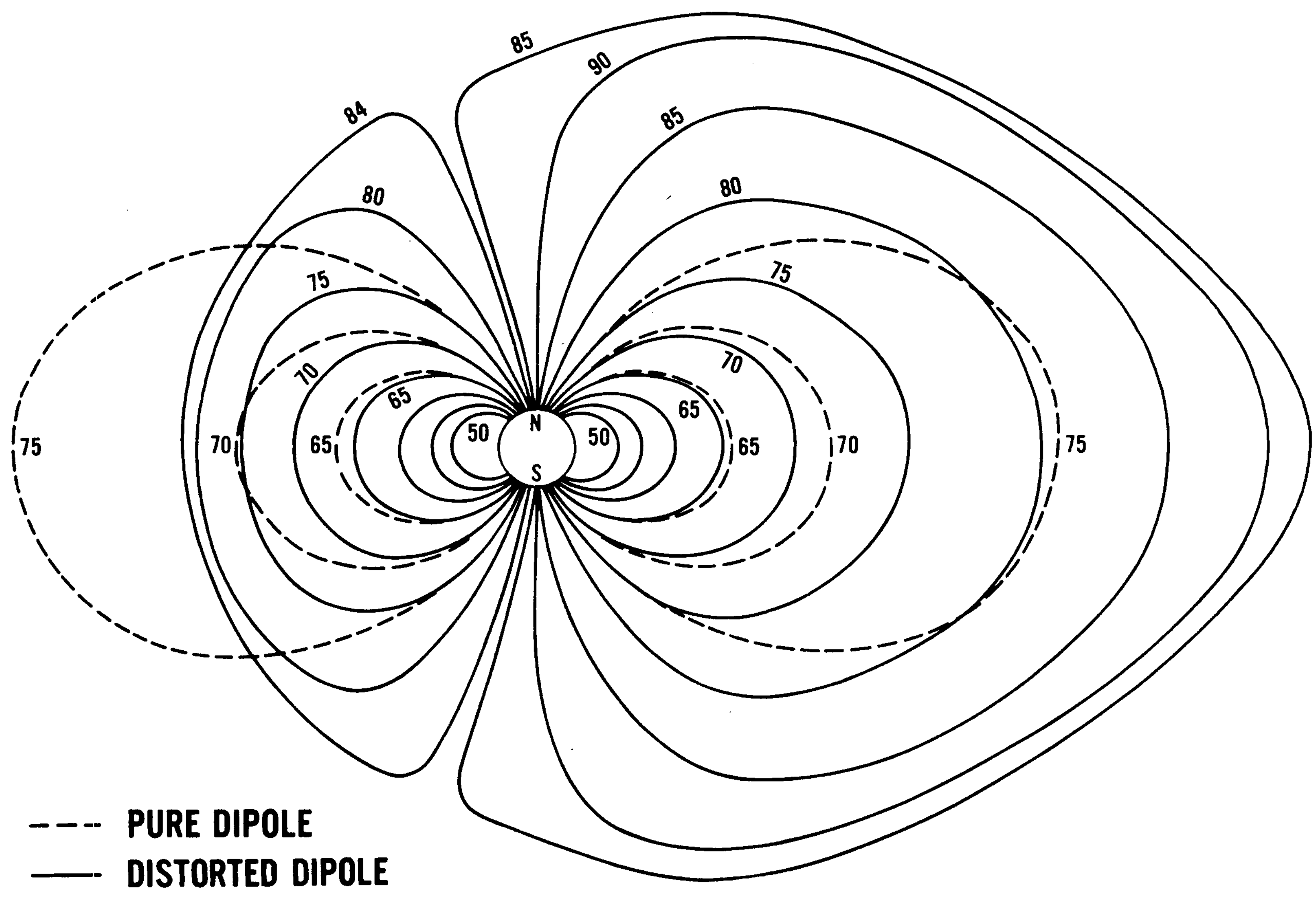


LATITUDE = 0°
NOON (φ=180°)
r_b= 10 R_E
X TOTAL
X DIPOLE
X SURF. CURR.
77γ
46γ
31γ
MAGNETIC FIELD (GAMMAS)
DISTANCE (EARTH RADII)
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

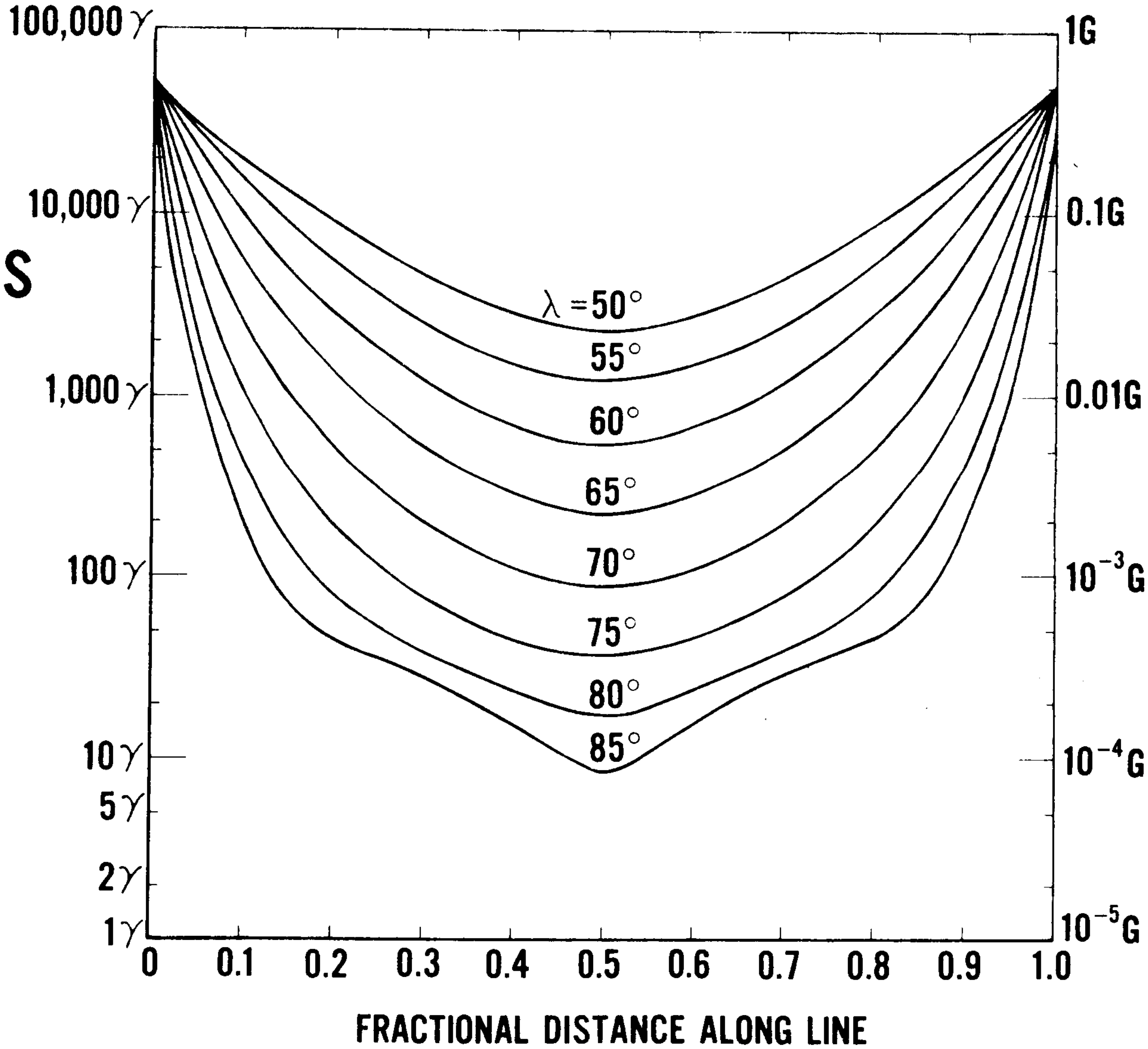

LATITUDE = 0°
6 P.M. (φ = 270°)
r_b = 10 R_E
X_{DIPOLE}
X_{TOTAL}
$X_{SURF.\ CURR.}$
MAGNETIC FIELD (GAMMAS)
DISTANCE (EARTH RADII)
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14


LATITUDE = 45°
NOON (φ = 180°)
r_b = 10 R_E
X_{DIPOLE}
X_{TOTAL}
Z_{DIPOLE}
Z_{TOTAL}
$X_{SURF.\ CURR.}$
$Z_{SURF.\ CURR.}$
MAGNETIC FIELD (GAMMAS)
DISTANCE (EARTH RADII)
150
100
50
0
-50
1
2
3
4
5
6
7
8
9
10
11
12
13
14

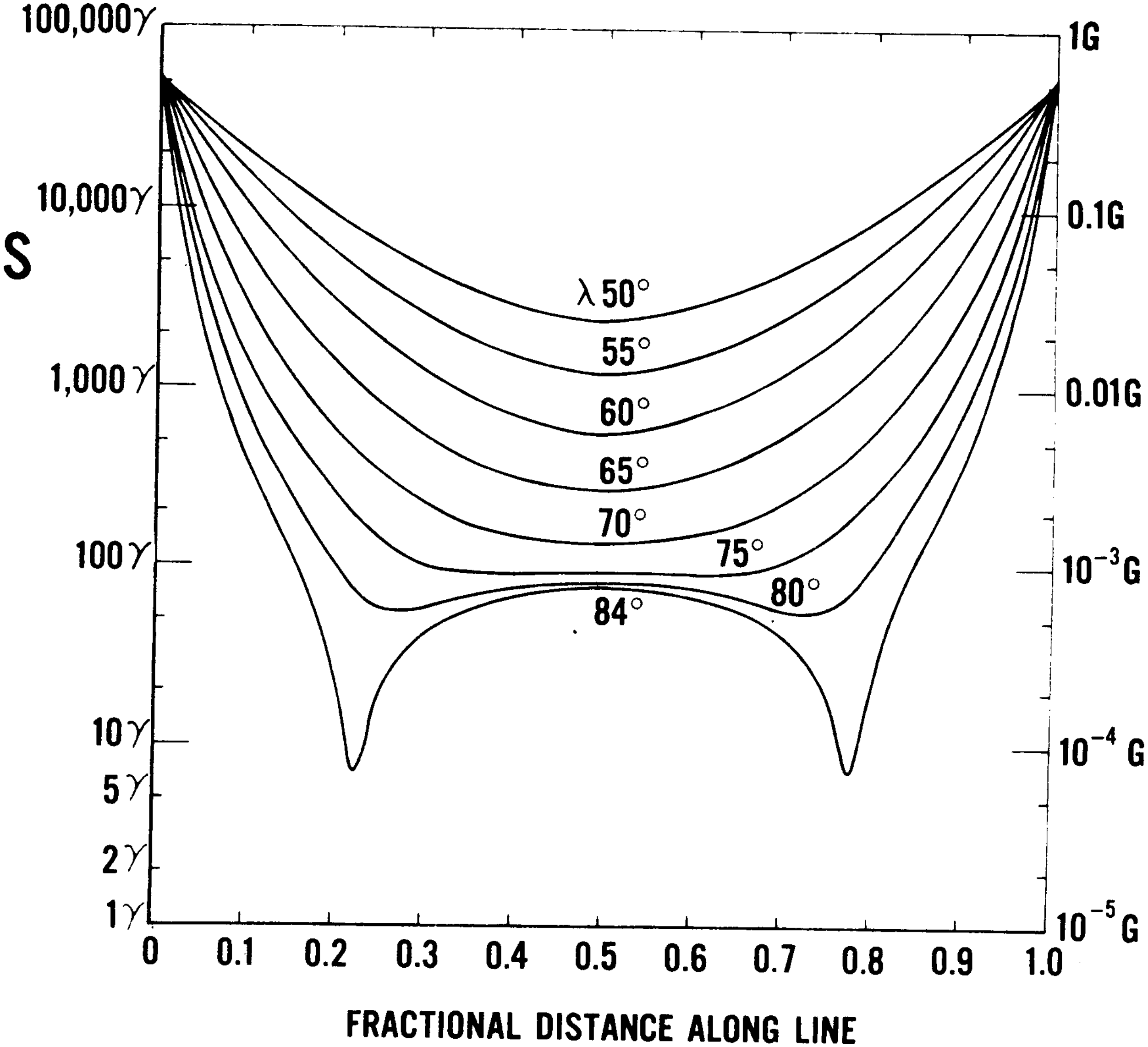
FIELD LINES IN NOON MERIDIAN PLANE



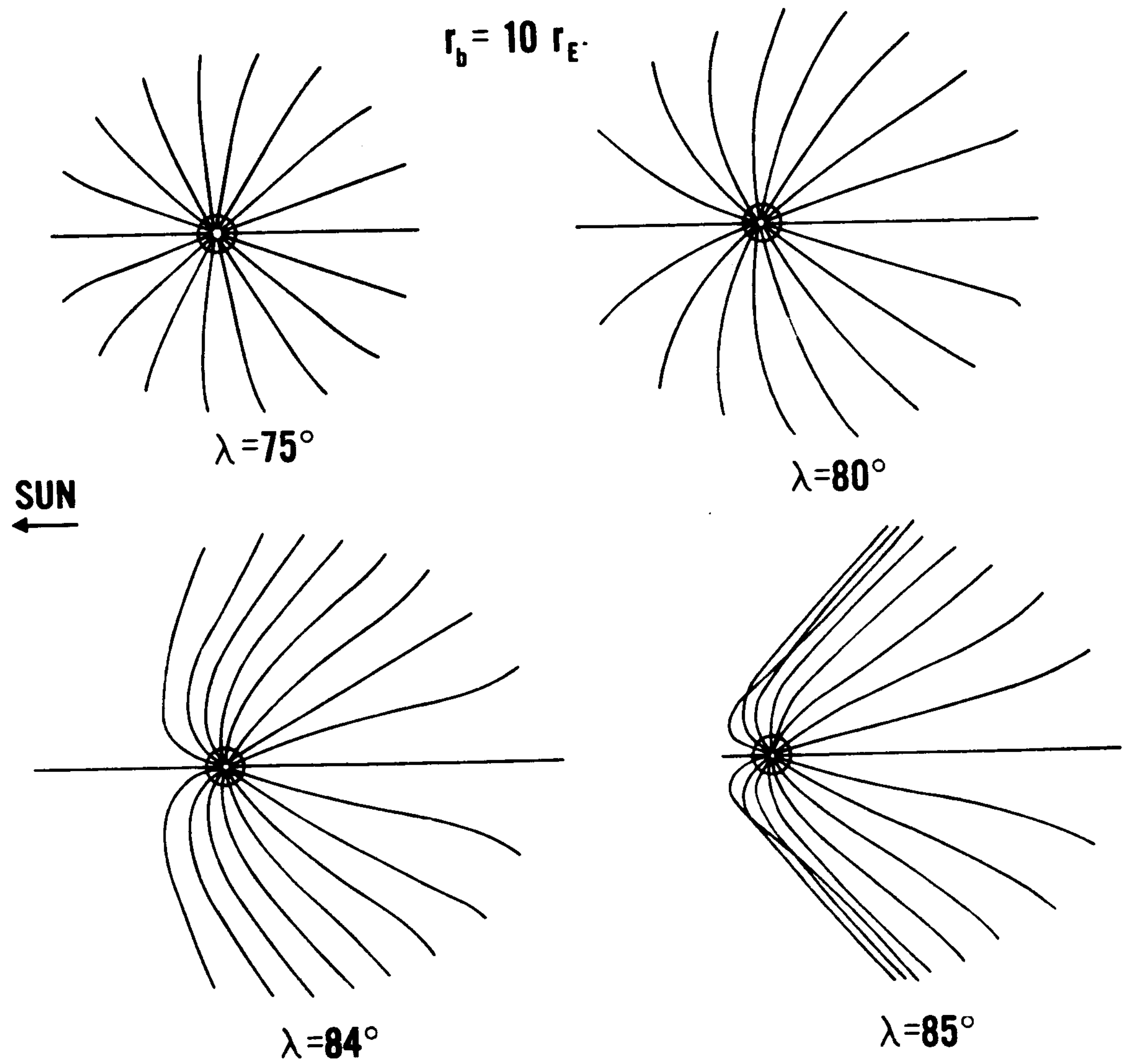
|B| ALONG FIELD LINES
DARK SIDE



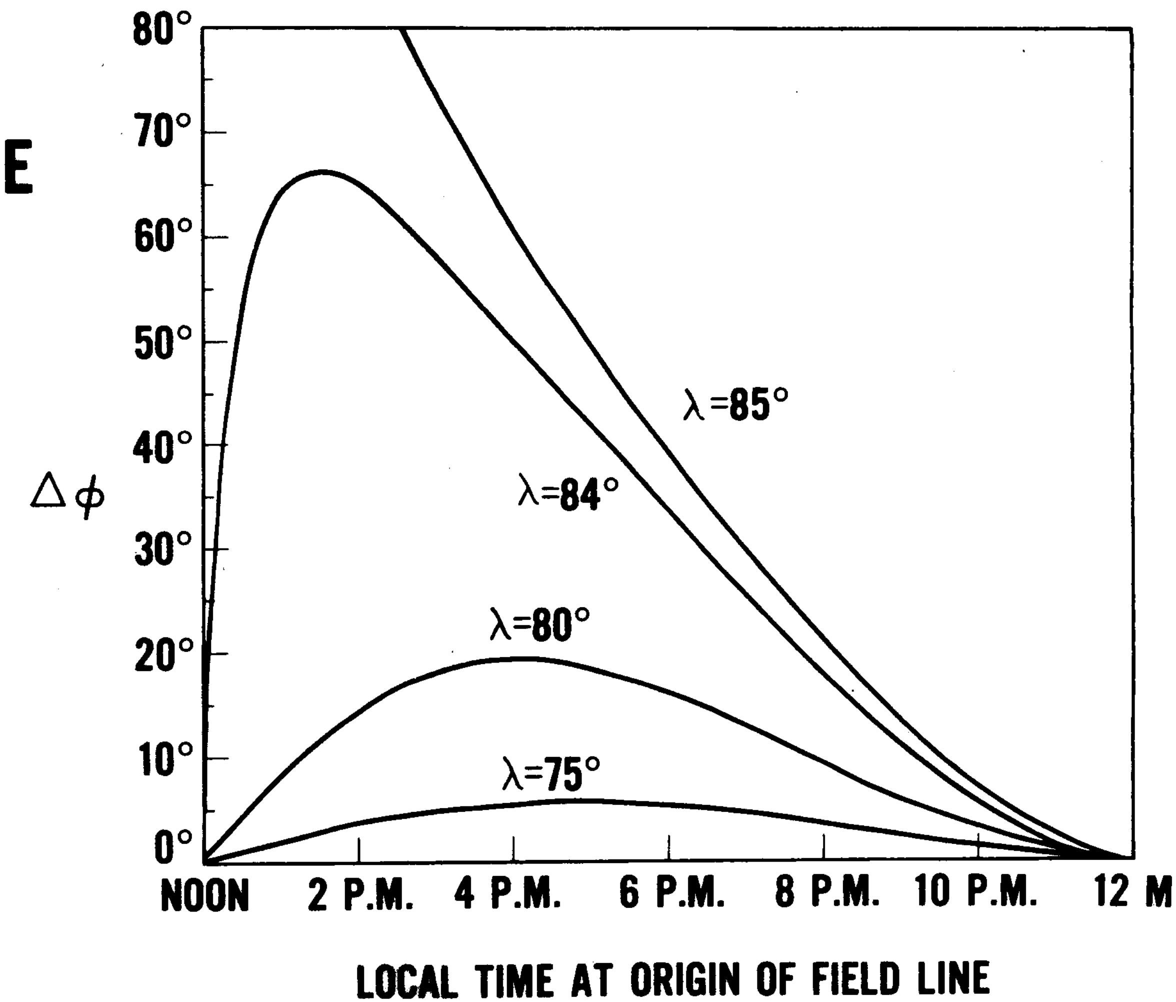
|B| ALONG FIELD LINES
LIGHT SIDE



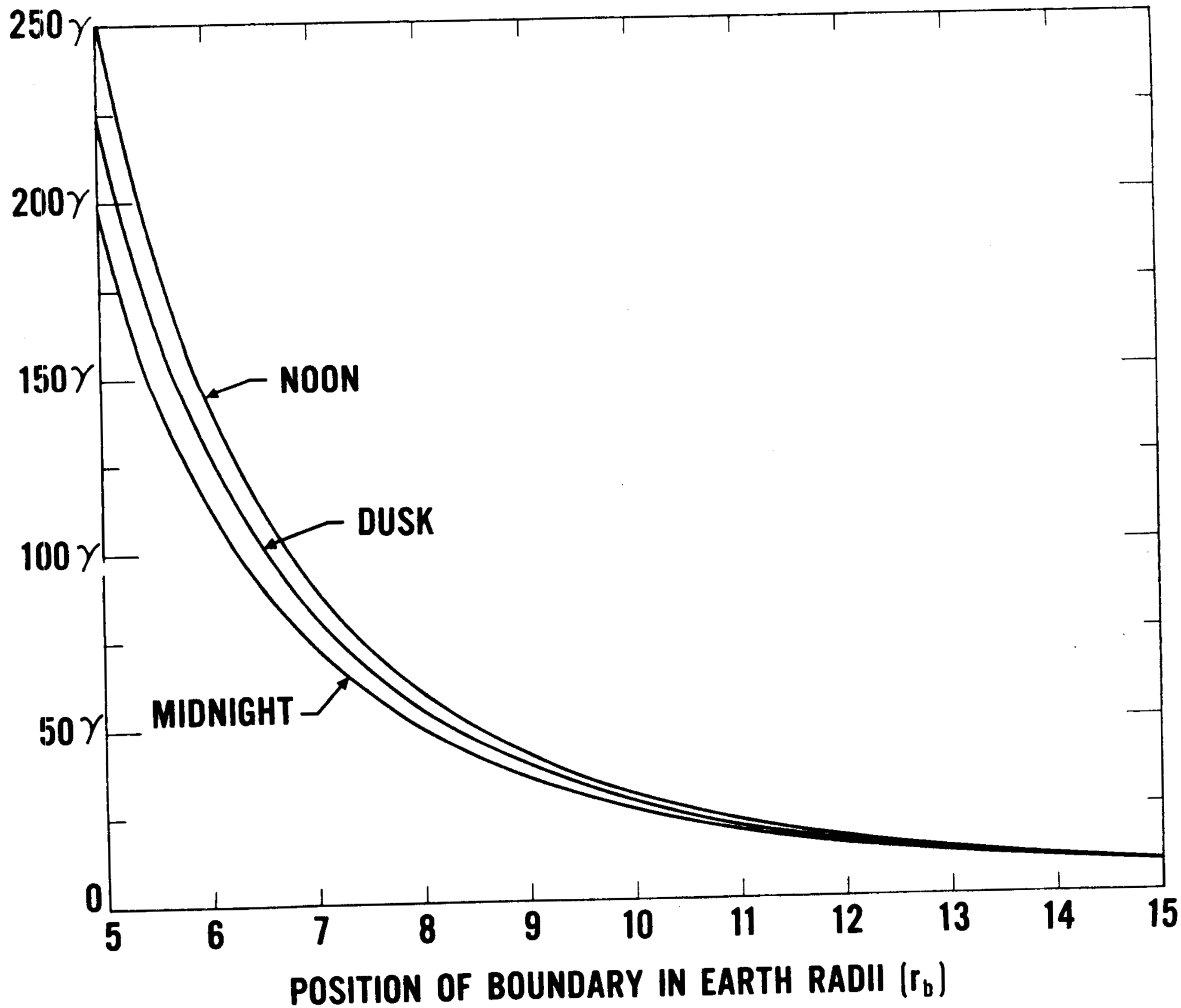
TOP VIEW OF FIELD LINES



LONGITUDINAL CHANGE
OF FIELD LINE
AT EQUATOR



SURFACE CURRENT FIELD AT EARTH'S SURFACE ALONG EQUATOR



SOLAR DAILY VARIATION
$(r_b = 10\ r_E)$